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Influence of Arctic Stratospheric Ozone on Surface Climate in CCMI models

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Abstract. The Northern Hemisphere and tropical circulation response to interannual variability in Arctic stratospheric ozone is analyzed in a set of the latest model simulations archived for the Chemistry-Climate Model Initiative (CCMI) project. All models simulate a connection between ozone variability and temperature/geopotential height in the lower stratosphere similar to that observed. A connection between Arctic ozone variability and polar cap sea-level pressure is also found, but additional analysis suggests that it is mediated by the dynamical variability that typically drives the anomalous ozone concentrations. The CCMI models also show a connection between Arctic stratospheric ozone and the El Niño Southern Oscillation (ENSO): the CCMI models show a tendency of Arctic stratospheric ozone variability to lead ENSO variability one to two years later. While this effect is much weaker than that observed, it is still statistically significant. Overall, Arctic stratospheric ozone is related to lower stratospheric variability and may also influence the surface in both polar and tropical latitudes, though these impacts can be masked by internal variability if data is only available for ~ 40 years.

1 Introduction

The stratospheric ozone layer not only protects life on Earth from solar ultraviolet radiation but also controls stratospheric temperature, which in turn affects tropospheric weather and climate (World Meteorological Organization, 2014). Stratospheric ozone was increasingly depleted in the last few decades of the twentieth century over many regions of the globe and is not expected to fully recover for many decades (World Meteorological Organization, 2014). Arctic stratospheric ozone (ASO) has been relatively spared from the worst ozone destruction, though during some winters depletion has been observed (Staehelin et al., 2001) comparable to that in the Antarctic (e.g. March of 2011, Manney et al., 2011). It is well established that ozone depletion in the Antarctic stratosphere affects surface climate (Polvani et al., 2011; Waugh et al., 2015), though a clear link between Arctic ozone depletion and surface climate has not yet been conclusively established.

Recent modeling studies have examined the possible connection between Arctic spring ozone and surface climate using a range of approaches, and obtained mixed results. Cheung et al. (2014) probed whether the extreme Arctic ozone depletion of

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2011 had an effect on tropospheric climate with the UK Met Office operational weather forecasting model. They found no improvement in spring tropospheric forecast skill when forcing the model with more realistic ozone concentrations as compared to climatological ozone. Karpechko et al. (2014) found a relationship between the 2011 low Arctic stratospheric ozone anomalies with tropospheric climate in atmospheric GCM simulations, but noted that specifying the ozone anomalies in isolation of sea surface temperature anomalies did not result in a significant surface impact. This sensitivity suggests that the radiative perturbation due to ozone requires tropospheric feedback in order to robustly modulate surface climate (e.g. Kirchner and Peters, 2003). Smith and Polvani (2014) found that only for a prescribed ozone forcing larger than that historically observed is the tropospheric response robust in their simulations. In contrast, the coupled chemistry-climate simulations of Calvo et al. (2015) include a robust stratospheric-tropospheric response in low versus high ozone years: a positive phase of the North Atlantic Oscillation, a poleward shift of the North Atlantic tropospheric jet, and corresponding regional surface temperature anomalies. Their study used an ensemble of simulations driven by historically observed ozone depleting substances. The fully-coupled approach of Calvo et al. (2015) allows consistency between the evolving ozone distributions and dynamical conditions among other differences in the model configuration, which may explain the differences between their conclusions and those of studies prescribing ozone concentrations. However, there is some ambiguity in the approach of Calvo et al. (2015) as to whether the surface anomalies are due to the ozone anomalies: ozone anomalies are usually accompanied by anomalies in the Arctic vortex (i.e. early or delayed breakup of the Arctic vortex for high ozone or low ozone respectively, Hurwitz et al., 2011) and vortex anomalies independent of ozone have been shown to influence surface conditions (Black and McDaniel, 2007; Ayarzagüena and Serrano, 2009; Hardiman et al., 2011). Hence to some degree the surface anomalies found by Calvo et al. (2015) may be related to the altered dynamical state of the vortex rather than ozone per se.

Two recent observational studies have also suggested that interannual variability in ozone can modify surface climate. Ivy et al. (2017) find that extreme Arctic stratospheric ozone (ASO) anomalies in March are associated with Northern Hemisphere tropospheric climate in spring (March-April) in specific regions of the Northern Hemisphere, with the effects generally consistent with the modeling study of Calvo et al. (2015). However, a delayed or advanced final warming of the Arctic vortex can lead to some of the surface impacts found by Ivy et al. (2017) (e.g. Black and McDaniel, 2007; Ayarzagüena and Serrano, 2009; Hardiman et al., 2011), and it is not clear whether the surface response is due to the dynamical impact from the final warming as opposed to the radiative impact of the ozone anomaly that typically accompanies a final warming. Finally, Xie et al. (2016) suggest that ASO anomalies influence sea level pressure anomalies over the North Pacific which in turn modulates subtropical sea surface temperatures. This subtropical sea surface temperature anomaly might then lead to improved predictability of the El Niño Southern Oscillation, though this response is delayed by a year for reasons not yet clear (Garfinkel, 2017).

Here we revisit the connection between boreal spring Arctic stratospheric ozone variability on interannual timescales and surface climate using the coupled ocean-atmosphere-chemistry models participating in the Chemistry-Climate Model Initiative (CCMI) project. We analyze ~ 1680 model-years of output data, which helps provide context for the associations evident in the relatively short observational record and in previous modeling studies which analyzed shorter simulations. We demonstrate that while Arctic ozone does appear to be associated with surface variability, the apparent connection is largely associated with the dynamical control of ozone in the lower stratosphere by the polar vortex. In addition, while Arctic ozone does appear to

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influence ENSO for up to two years later, this association is much weaker than that observed. Overall, while Arctic stratospheric ozone may lead to surface impacts, these impacts are generally weak and can be masked by internal variability if data is only available for ~ 40 years.

2 Data and Methods

2.1 Data

We analyze the Modern-era retrospective analysis for research and applications reanalysis (MERRA Rienecker et al., 2011), the merged ozone product from SWOOSH v2.5 (Davis et al., 2016), and output from atmospheric chemistry-climate-ocean general circulation models (CCMs) participating in the CCMI project.

CCMI was jointly launched by the Stratosphere-troposphere Processes And their Role in Climate (SPARC) and the International Global Atmospheric Chemistry (IGAC) to better understand chemistry-climate interactions in the recent past and future climate (Eyring et al., 2013; Morgenstern et al., 2017). This modeling effort is an extension of CCMVal2 (SPARC-CCMVal, 2010), but utilizes up-to-date CCMs. The CCMI models used in this study are listed in Table 1. We consider the Ref-C2 simulations from models that are coupled to an interactive ocean and have uploaded their data to the British Antarctic Data Center server, and we also include the National Center for Atmospheric Research (NCAR) models (Morgenstern et al., 2017). As we are interested in the surface impact of ozone anomalies over both land and ocean areas, we consider coupled ocean-atmosphere models only where surface impacts can occur in a self-consistent manner with the stratospheric ozone variability. In contrast, nearly all of the CCMVal2 models imposed sea surface temperatures (Morgenstern et al., 2010). The standard deviation of SST variability in the Nino3.4 region for the models is shown in Figure 1, and the the amount of variability in all models considered here is within 50% of that observed. One additional CCMI model included a coupled ocean (CHASER), however the ENSO in this model is too weak: the standard deviation of the Nino3.4 index in this model is 0.2 Kelvin as compared to the observed value of 0.85 Kelvin, and we therefore exclude it from this paper. Finally, we have examined the power spectral density for SSTs in the Nino3.4 region in these models, and in all cases there is a peak between 2 and 5 years (not shown).

2.2 Methods

Most models used in this study archive data over a period of 140 years, while the observational record available in either MERRA or SWOOSH extends for less than 40 years. To allow for a more natural comparison of model output to observations we divide the output from the CCMI models into periods of 40 years, to more closely match the data availability of MERRA/SWOOSH. Specifically, we divide the data of each of the CCMI models into three time periods: 1970-2010, 2011-2051, 2052-2092. The net effect is that we have 42 model-chunks of identical size (40 years) that we can meaningfully compare to observations. For each data source we analyze the variables: temperature, geopotential height, surface air pressure, and the zonal mean ozone volume mixing ratio. We define a zonal mean index of Arctic stratospheric ozone (ASO) following Xie et al. (2016) as the area-weighted average of zonal mean ozone from 60°N to 90°N and mass-weighted from 150hPa to 50hPa. For

Table 1: CCMI models used

data source	ensemble members	reference
MERRA/SWOOSH	1	Rienecker et al. (2011); Davis et al. (2016)
NIWA	5	Morgenstern et al. (2009)
CESM1 WACCM	3	Garcia et al. (2017)
CESM1 CAM4-chem	3	Tilmes et al. (2016)
HadGem3-ES	1	Hardiman et al. (2017)
MRI-ESM1r1	1	Yukimoto et al. (2012)
EMAC	1	Jöckel et al. (2016)

Table 1.

ENSO we use surface air temperature in the region bounded by 5°S-5°N and 190°E-240°(i.e. the Nino3.4 region), as sea surface temperature was not available for all models at the time we downloaded data. Note that the observed negative correlation between ENSO and ASO at a lag of 20 months is essentially unchanged if we use air temperature as opposed to sea surface temperature.

This study focuses on the impact of ASO on the troposphere on interannual timescales, and in order to remove any impacts on longer timescales due to climate change or ozone depleting substances, we first use multiple linear regression to remove the linear variability associated with greenhouse gases and ozone depleting substances from our time series. We use the equivalent CO2 from the RCP6.0 scenario to track greenhouse gas concentrations (Meinshausen et al., 2011) and the effective equivalent stratospheric chlorine (EESC) following Newman et al. (2007, Eq.1, assuming a 5.5yr age-spectrum) to track ozone depleting substances on multi-decadal timescales. For certain models, limited data was either missing, corrupted, or non-physical, and such data was replaced by the monthly average of the previous 15 years and the next 15 years (if this period extends beyond the start or end date of data, we use the maximal number of years available). For example, if the value for March 2000 was corrupted it was replaced by the average of all March values from 1985 to 1999 and 2001 to 2015, before performing the multiple linear regression. After the multiple linear regression is performed these values are returned to missing.

The statistical significance of the correlation between two auto-correlated time series is computed using the two-tailed Student's t-test at the 95% confidence level: The effective number of degrees of freedom N^{eff} used in the Student's-t test is approximated following Pyper and Peterman (1998), Li et al. (2013), and Li et al. (2012):

$$N^{eff} = \frac{1}{N} + \frac{2}{N} * \sum_{j=1}^{N/4} \frac{N-j}{N} * \rho_{xx}(j) * \rho_{yy}(j) \tag{1}$$

where N is the sample size, and ρ_{xx} and ρ_{yy} are the auto-correlation vectors of ENSO and ASO. The summation in equation 1 is performed up to $N/4$ following the recommendations of Pyper and Peterman (1998). In addition, Pyper and Peterman (1998) find that substituting N^{eff} with N^{eff}-2 provided a better balance between estimates of N^{eff} and error rates, thus improving the validity of the student's t-test.

3 Effect of Arctic stratospheric ozone (ASO) on polar surface climate

We first consider the connection between ASO and zonally averaged temperature and geopotential height (Figure 2). Higher values of ASO are associated with elevated geopotential height and warmer temperature over the polar lower and mid-stratosphere and lower geopotential heights, and colder temperatures in the tropical lower and mid-stratosphere in reanalysis data (Figures 2ab). This effect is consistent with previous work that has shown that transport controls lower stratospheric ozone concentrations (Douglass et al., 1985; Hartmann, 1981; Rood and Douglass, 1985; Hartmann and Garcia, 1979; Silverman et al., 2017).

The CCMI ensemble-mean (i.e. the mean of all 42 sub-models) correlation between March ASO and March geopotential height and temperature is shown in Figure 3. The CCMI models capture the connection between the two phenomena, and the magnitude is similar to that observed. However there are differences in the location and magnitude of the extrema, and in order to more meaningfully compare the relatively short observational record to the model output, we divide the model output into 40 year chunks (see section 2). Figure 4a compares the correlation of ASO with 100hPa polar cap temperature (on the x-axis) and with 100hPa geopotential height (y-axis) in March. Each 40-year chunk of each model is indicated with a single x, the reanalysis is indicated with a green asterisk. Models with a tighter connection between ASO and polar cap temperatures also feature a tighter connection between ASO and polar cap geopotential height, and the connection in reanalysis data falls well within that simulated by CCMI models. Results are similar for April as well (Figure 4b). This validates the fidelity of the coupling between these phenomena in the CCMI models. It is beyond the scope of this paper (which focuses on monthly mean data) to determine the dominant direction of causality, though process-driven studies of observational data have indicated that lower stratospheric ASO anomalies are driven by transport (e.g. Douglass et al., 1985). Anomalous transport can occur both on large spatial scales where the same wind field that advects the ozone across the vortex barrier into the pole also leads to a warmer pole, and also on smaller scales where the causality of the connection between zonal mean temperature and ASO is less obvious.

Does ASO affect the troposphere? Figure 5a shows the correlation of polar cap sea level pressure with ASO in March. Higher levels of ASO are associated with higher sea level pressure over the polar cap and over Greenland and with lower SLP further south in the Atlantic sector; overall the pattern resembles the negative phase of the North Atlantic Oscillation (consistent with Ivy et al., 2017, the feature over the North Pacific will be discussed in section 4). This relationship can be summarized by computing the correlation of sea level pressure area-weighted from 80N and poleward with ASO, and we show the result from MERRA and from all of the CCMI models on the x-axis of Figure 4c. The correlation in MERRA data is 0.37 (statistically significant at the 95% level), which is larger than in most, but not all, of the CCMI models. CCMI models show a stronger relationship in April instead (Figure 4d); the mean correlation across all models jumps from 0.09 in March to 0.17 in April. Model 40-year chunks in which the connection between ASO with stratospheric polar cap height is stronger also simulate a stronger connection between ASO and polar cap SLP. Specifically, the correlation between these two is 0.54 in March and 0.60 in April (Figure 4cd), though clear outliers do exist. Hence while the CCMI multi-model mean simulates a weaker connection between ASO and polar cap SLP than is observed, the observed association is enveloped by the range of CCMI models and the relationship between ASO and polar cap SLP in the CCMI models is still statistically significant at the 95% level (in agreement with Calvo et al., 2015).

However, there is ambiguity as to whether the surface anomalies are due to the ozone anomalies: ozone anomalies are usually accompanied by anomalies in the Arctic vortex (Figure 4ab) and previous work has shown that spring Arctic vortex anomalies independent of ozone can influence surface conditions (Black and McDaniel, 2007; Ayarzagüena and Serrano, 2009; Hardiman et al., 2011). We now demonstrate that vortex anomalies are associated with polar cap SLP anomalies in the CCMI models as well, and then try to isolate statistically the relative importance of ASO.

We first show that stratospheric polar cap geopotential height and temperature are even more strongly related to tropospheric variability than is ASO. Figure 4ef compares the correlation of 100hPa polar cap geopotential height with polar cap SLP on the x-axis with the correlation of 100hPa polar cap temperature with polar cap SLP on the y-axis. The mean correlation of 100hPa polar cap geopotential height with polar cap SLP is more than double the corresponding correlation of polar cap SLP with ASO (0.55 as compared to 0.09 in March, and 0.40 as compared to 0.17 in April). The correlation of ASO with polar cap SLP is also weaker than that of 100hPa polar cap temperature with polar cap SLP.

It could well be that the apparent connection between ASO and polar cap SLP is just a byproduct of the tight connection between polar cap stratospheric geopotential height with both parameters, rather than a direct connection. We address this issue by using linear regression to statistically remove the portion of polar cap SLP variability and ASO variability that is linearly related to stratospheric polar cap geopotential height from each model, and then consider whether there remains any lingering connection between ASO and polar cap SLP. The results are displayed on the x-axis of the bottom row of Figure 4. The correlation of ASO with polar cap SLP is now negative both for most CCMI models and also for observations - high ozone is associated with lower heights over the pole - opposite of the relationship when Z was not regressed out. This indicates that there is no distinct pathway whereby ASO affects the polar troposphere, but rather it affects the polar troposphere through its coupling to the dynamics of the lower stratospheric polar vortex.

4 Effect of Arctic stratospheric ozone (ASO) on ENSO

Xie et al. (2016) recently suggested that Arctic stratospheric ozone anomalies influence North Pacific sea level pressure patterns which in turn affects subtropical sea surface temperatures, and the subtropical sea surface temperature anomalies modulate ENSO through the seasonal footprinting mechanism approximately 20 months later. Their conclusions were based on the limited observational record and model experiments with one model, and we now consider whether CCMI models capture

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this association in order to assess the robustness of this effect. The CCMI models included in our study contain both ozone variability and an internally generated ENSO (Figure 1), hence they simulate the relevant underlying processes.

We begin with the lagged-correlation of ASO and ENSO for lags ranging between -40 to 40 months using MERRA/SWOOSH data (figure 6a) following Xie et al. (2016) in order to establish context for the CCMI models. ENSO is positively correlated with ASO seven months later (at lag equal to -7), such that e.g. El Niño leads to more ozone seven months later. The more robust relationship is a negative correlation between ASO and ENSO 20 months later (at lag equal to 20) such that e.g. more ASO leads to a La Niña 20 months later. This relationship is nearly statistically significant at the 95% level using a two-tailed Student's t-test. Xie et al. (2016) noted that the strongest observed connection between ASO and ENSO is March ASO with ENSO 20 months later, and hence we show the lagged-correlation between March ASO and ENSO in figure 6b. The correlation of ENSO in January with ASO two months later in March is 0.2, and the correlation of ASO in March with ENSO $\sim$ 18 months later is nearly -0.5. All of these relationships are in agreement with Xie et al. (2016).

Do the CCMI models capture these relationships between ASO and ENSO? We first focus on the multi-model mean lagged correlation between ENSO and ASO in Figure 7. The lagged-correlation function between ASO and ENSO reveals the same general lead/lag behavior as seen in the MERRA/SWOOSH model but generally with much weaker correlations. The positive correlation at lag=-4 (Figure 7a) exceeds 0.1, corresponding to El Niño leading to enhanced ASO after 4 months, and this effect is highly statistically significant and is consistent with that found in CCMVal models (Cagnazzo et al., 2009). Hence the models are able to capture the forcing of ASO anomalies by ENSO, with El Niño leading to enhanced ASO and La Niña leading to reduced ozone (Cagnazzo et al., 2009).

The lagged-correlation also revealed a negative peak at a lag of 10 months, and statistical significance is maintained from a lag of 6 months up to a lag of 22 months. This result is in agreement with the feature seen in MERRA/SWOOSH and Xie et al. (2016). However the correlation at positive lags in the multi-model mean is a factor of five weaker than that observed; furthermore, the correlation is strongest not 20 months after the ASO anomalies, but rather 10 months later. We have also computed the correlation coefficients between March ASO and ENSO in order to focus on the season where the observed relationship peaks (Figure 7b). A statistically significant negative correlation is found when ASO lead ENSO by 8-14 months. An additional, smaller yet also statistically significant, negative local peak is obtained at a lag of 20 month (at Nov(1) on Figure 7b), qualitatively in agreement with the observed relationship but much weaker in magnitude.

The multi-model mean lagged-correlations differ from that observed in two aspects: they are weaker and also peak at earlier lags. This does not necessarily imply that the models are inconsistent with the observed effect, as some models do show a relationship that resembles that observed. To highlight this effect, we compare 40-year sub-samples from the same model in the bottom four rows of Figure 6. Figure 6cegi is constructed analogously to Figure 7, but it focuses on two different 40 year sub-samples from the same model integration for two models. These two sub-samples indicate an opposite lead/lag relationship between ENSO and ASO between adjacent sub-samples for the same model integration. For example, WACCM run #3 over the years 2011-2051 indicates a similar lead-lag relationship as the one observed in MERRA/SWOOSH (figure 6c). Yet, over the years 2052-2092 (Figure 6e), the exact same model integration suggests that any apparent modulation of ENSO by ASO is weak and only appears at much shorter lags. Another example for the intra-model variability is evident in the results of the NIWA-R3 model (Figure 6gi). NIWA-R3 simulates a lead-lag relationship that does not resemble the observed one over the years 2011-2051, whereas for the years 2052-2092 the lead/lag relationship shows some similarities. Thus, these two sub-samples of the same model are different from each other and therefore gives different results when comparing to MERRA/SWOOSH. Similar results are evident if we focus on the lagged correlation of March ASO with ENSO (right column of Figure 6).

These differences are not associated with stratospheric variability, as the correlation between ASO and stratospheric temperature and geopotential height is qualitatively similar in these experiments. Specifically, these specific sub-samples from WACCM (compare Figures 2cd to Figures 2ef) and NIWA (compare Figures 2gh to Figures 2ij) both show a positive correlation between ASO and polar cap geopotential and temperature. Hence internal tropospheric or oceanic variability appears to be the source of the difference in the connection between ASO and ENSO. That internal tropospheric or oceanic variability can mask the connection between ASO and ENSO over a 40 year period suggests that the observational polar ozone record is too short to reach firm conclusions as to the connection between ENSO and ASO. More specifically, it is possible that internal climate variability could have contributed to the apparent observed effect. The possible role of internal variability can be reduced as much as possible by computing the multi-model mean of the correlations (by averaging over all lagged-correlation coefficients), and as discussed above the multi-model mean correlation is much weaker and peaks sooner than that observed.

Xie et al. (2016) propose a specific mechanism between ASO and ENSO, and we now evaluate whether this mechanism is operating in the CCMI models. Specifically, they argue that higher ASO leads to higher SLP over the North Pacific in March and April (red box on Figure 5ab), which directly leads to warmer sea surface temperatures in the subtropical North Pacific (red box on Figure 5c) as the cold continental winds off Eurasia are weakened. This warming of the subtropical North Pacific then leads to a La Niña event due to the seasonal footprinting mechanism (Vimont et al., 2003). It is difficult to deduce any evidence for these effects in the multi-model mean SLP and sea surface temperature response (Figure 8), though the multi-model mean correlation between ASO and ENSO was also weak. Even if we focus on the model sub-samples that did succeed in capturing a relationship between ASO and ENSO (e.g. WACCM run #3 for the years 2011-2051 and NIWA-R3 over the years 2052-2092), there is no better agreement with the observed SLP and surface temperature anomalies than in the model sub-samples that failed to capture the observed relationship between ASO and ENSO (Figure 5). The correlation between April surface temperature in the red boxed region of Figure 5c with March ASO averaged across all CCMI models is 0.02, and while individual model sub-samples simulate correlations as large as the observed correlation of 0.3, there is no significant relationship between the models that simulate greater warming in this region in response to enhanced ASO and the relationship between ASO and ENSO 20 months later. Hence there is no evidence that the mechanism of Xie et al. (2016) is present in the CCMI models.

One might hypothesize that the apparent relationship between ASO and ENSO ~ 20 months later is driven by the autocorrelation of ENSO: El Niño (which typically drives higher ASO) is often followed by a La Niña event a year or two later, and one might therefore suppose that the La Niña event 20 months after the high values of ASO is due to internal oceanic ENSO dynamics and does not involve the stratosphere (e.g. Garfinkel, 2017). However this hypothesis can be negated as follows. Suppose one was to build a linear regression model where the ENSO state at lag e.g. 20 months is predicted by the state of

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ENSO at lag 0 and also by the value of ASO at lag 3 months. It can be shown that for ASO to add value to the linear regression model, the correlation between ASO at lag 3 months with ENSO must satisfy: (Hartmann, 2016).

$$|r(ASO^3, ENSO^y)|_{minuseful} > |r(ENSO, ENSO^y) r(ENSO, ASO^3)| \tag{2}$$

where $r(ASO^3, ENSO^y)$ is the correlation coefficient when ASO at lag 3 months is leading ENSO by y (e.g. 20) months, $r(ENSO, ASO^3)$ is the correlation coefficient when ASO is lagging ENSO by 3 month, and $r(ENSO^y, ENSO)$ is the auto-correlation of ENSO at lag y (e.g. 20) months, though y can in principle be 4 months or larger. The red lines in Figure 6a and Figure 7a indicate the minimally useful correlation $r(ASO^3, ENSO^y)|_{minuseful}$ between ASO and ENSO for a range of y values, and for both observations and the CCMI models the actual correlation between ASO and ENSO far-exceeds the minimally useful one. Hence the apparent connection between ASO and ENSO ~20 months later is not just an artifact of ENSO auto-correlation.

The association between ASO and ENSO in the CCMI models does not appear to be related to dynamical changes in the Arctic vortex. The red lines in Figure 6b and Figure 7b indicate the lagged correlation between March 100hPa polar cap geopotential height and ENSO. El Niño is associated with higher March geopotential height at zero lag, but there is no indication that higher geopotential height (typically associated with high values of ASO) leads to La Niña a year later. (Recall that polar cap SLP is more strongly affected by polar cap geopotential height than ASO.) This suggests a possible direct radiative impact of ASO on ENSO, though this speculation should be explored for future work.

Overall, the CCMI models do show a tendency of ASO variability to lead ENSO variability, but the effect is much weaker than that observed. This does not imply that the models are inconsistent with observations, as individual models do capture associations as strong as that observed. Rather, internal climate variability could be contributing to the apparent observed connection between ASO and ENSO.

5 Conclusions

The effects of Antarctic stratospheric ozone depletion on surface climate are well studied and have been shown to play a dominant role in Southern Hemisphere surface climate (Polvani et al., 2011; World Meteorological Organization, 2014; Waugh et al., 2015). While trends in Arctic stratospheric ozone (ASO) are weak, interannual variability in the Arctic is larger than in the Antarctic. However, the tropospheric impacts of this interannual variability in the Arctic stratospheric ozone layer have proven difficult to isolate, with different studies reaching opposite conclusions. Here we use the CCMI models to establish context for the observed connection between interannual ASO changes and polar tropospheric variability and ENSO.

Increased Arctic stratospheric ozone is associated with an increase in both polar cap temperatures and geopotential height over the polar lower and mid-stratosphere, in the CCMI models. Models with a stronger connection between ASO and polar cap temperatures also tend to simulate a stronger connection between the ASO and polar cap geopotential height. The strength of the connection between ASO and polar stratospheric temperature and height in the CCMI models straddles the strength of the observed connection between ASO and polar stratospheric temperatures and heights, suggesting that there is no discrepancy between the models and the observations.

ASO was also found to be significantly correlated with polar cap sea level pressure, in agreement with Calvo et al. (2015). However, the proximate cause of this surface impact is ambiguous as polar cap height anomalies can also lead to surface impacts. In fact, the association between polar cap sea level pressure and 100hPa polar cap geopotential height is stronger than that between polar cap sea level pressure and ASO, and if we regress out from polar cap sea level pressure any linear influence associated with 100hPa polar cap geopotential height, then there is no apparent relationship with ASO. This suggests that there is no distinct effect of ASO on the polar troposphere per se, and rather the connection between ASO and tropospheric variability is mediated through its covariability with the Arctic stratospheric vortex. The presence of realistic coupling between ozone and wind/temperature fields may account for the difference in conclusion between the study of Calvo et al. (2015) - who find a robust connection between ASO and the surface in a model which simulates ozone-dynamics interactions - and those of Cheung et al. (2014), Karpechko et al. (2014), and Smith and Polvani (2014) who imposed an fixed ozone perturbation decoupled from the dynamics in the stratosphere and find little tropospheric response.

Enhanced ASO appears to lead to La Niña 10 to 20 months later in both observations (in agreement with Xie et al. (2016)) and in the CCMI models, though the association in the CCMI models is much weaker than that observed and strongest at earlier lags. This relative weakness in the CCMI models is not necessarily due to model deficiencies, as the exact same CCMI model in the same integration can alternately simulate an association quantitatively similar to that observed or no association. Rather, internal climate variability can cloud any connection between ENSO and ASO when only 40 years of data are available, and much longer time-periods are needed to average over the large internal variability present.

This work raises several questions for future work. Establishing the direction of causality between stratospheric polar cap ozone and temperature/height anomalies in the CCMI is beyond the scope of this work, as daily data is needed to resolve the key processes. However previous work has suggested that dynamical transport drives ozone anomalies in the lower stratosphere (Douglass et al. (1985), Hartmann (1981), Rood and Douglass (1985), Hartmann and Garcia (1979), Silverman et al. (2017)). Such transport occurs in large scale eddies and in polar downwelling that includes a balanced temperature perturbation, and also in smaller scale mixing across the vortex edge where the wind field and temperature field are not necessarily balanced. The subpolar tropospheric impact of ASO anomalies in the CCMI models can be accounted for by the polar cap height perturbation, however the effect of ASO on ENSO did not appear to be related to any connection between ASO and polar cap geopotential height. Indeed, the mechanism linking ASO and ENSO in the CCMI models is unclear: there is little evidence for the specific mechanism proposed by Xie et al. (2016) and the effect is much stronger than would be expected if it was due solely to the auto-correlation of ENSO. Radiative effects have been demonstrated to be important for the connection between the solar cycle and SST anomalies that resemble ENSO (Meehl et al., 2009), and it is possible such a pathway may be important here as well. Finally, it is conceivable that the range of variability in stratospheric dynamics (i.e. the NAM) may be larger if ozone is interactive than when it is not, as a similar effect appears to be present in the Southern Hemisphere (Dennison et al., 2015).

Overall, (1) there is a strong connection between ASO and lower stratospheric temperature and geopotential height, and this connection likely mediates the connection between ASO and tropospheric changes; (2) the CCMI models capture most aspects of the connections that have been found in observations though not necessarily with the same magnitude as that observed,

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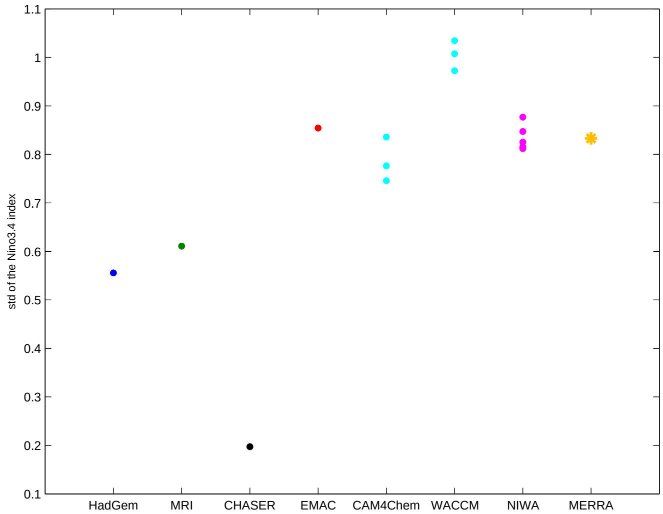

Figure 1. Standard deviation of the Nino3.4 index in the CCMI models. The multiple dots for NIWA, WACCM and CAM4Chem represent different integrations of the same model. The standard deviations in CHASER is much less than that observed, and hence this model was excluded from further analysis.

with differences possibly due to internal variability; and (3) ASO may be helpful for predicting future ENSO events but any additional prediction skill will be modest at best.

Author contributions. OH performed all data analysis and helped prepare the manuscript. CIG helped prepare the manuscript and provided overarching guidance and ideas. The other co-authors carried out the numerical experiments and provided feedback on the paper.

6 acknowledgment

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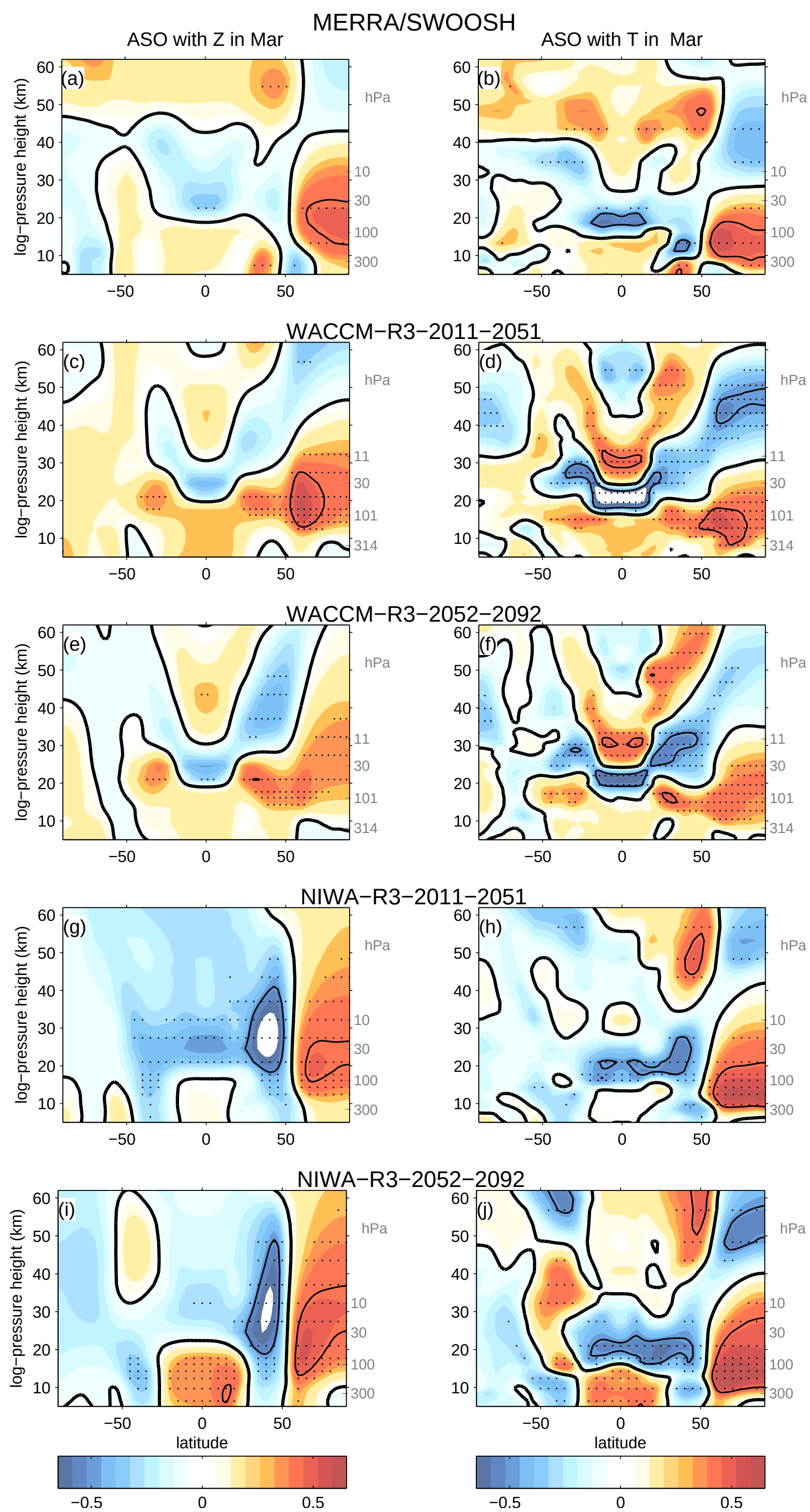

Figure 2. Correlation coefficients between ASO and geopotential height (left column) and between ASO and temperature (right column) for each of the examined data sources: (a-b) MERRA/SWOOSH, (c-f) WACCM-R3, (g-j) NIWA-R3. The black dot represents the locations in which correlations are statistically significant at the 95% level (see section 2.2). The zero line is thick black, and correlations of ±0.5 are thin black. The contour interval is 0.065

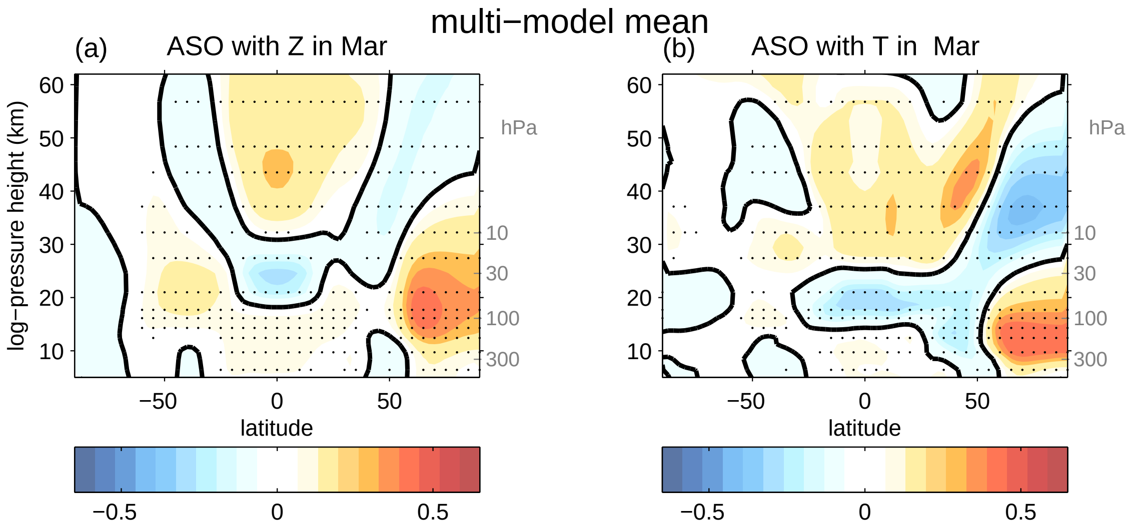

Figure 3. As in Figure 2 but for the multi-model mean

OM and GZ acknowledge the UK Met Office for use of the Unified Model, the NZ Government's Strategic Science Investment Fund (SSIF), and the contribution of NeSI high- performance computing facilities to the results of this research (https://www.nesi.org.nz). OM also acknowledges funding by the New Zealand Royal Society Marsden Fund (grant 12-NIW-006).

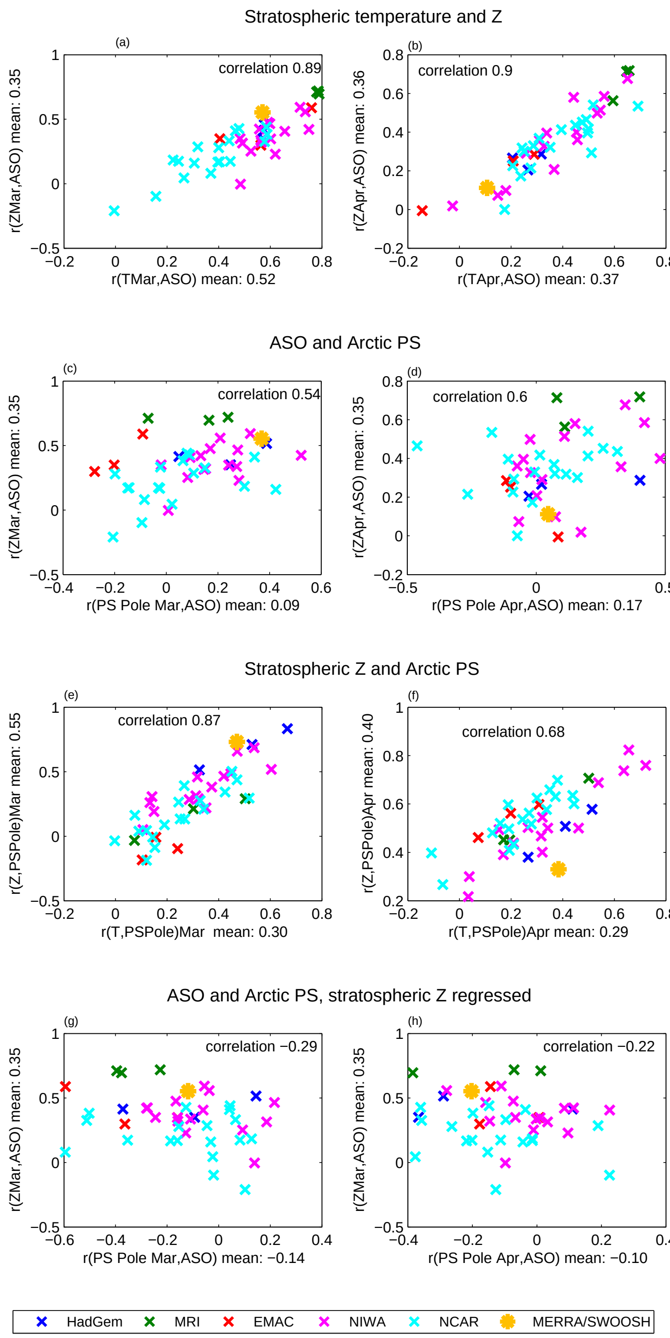

Figure 4. The connection between correlations of ASO and various stratospheric and tropospheric measures. In each subplot the X- and Y-axis represent correlation of two measures. Each x represents a different 40 year chunk of model output, and MERRA is represented by asterisks. The first row compares the correlation of ASO with polar cap startospheric temperature(T) with the correlation of ASO with polar cap geopotential height(Z) in (a) March and in (b) April. The second row compares the correlations of ASO and polar cap height (Z) with ASO and polar cap sea-level pressure(PS). The third row compares the correlations of polar cap Z and PS with polar cap T with PS. The forth and final row is similar to the second row except that polar cap Z was regressed out.

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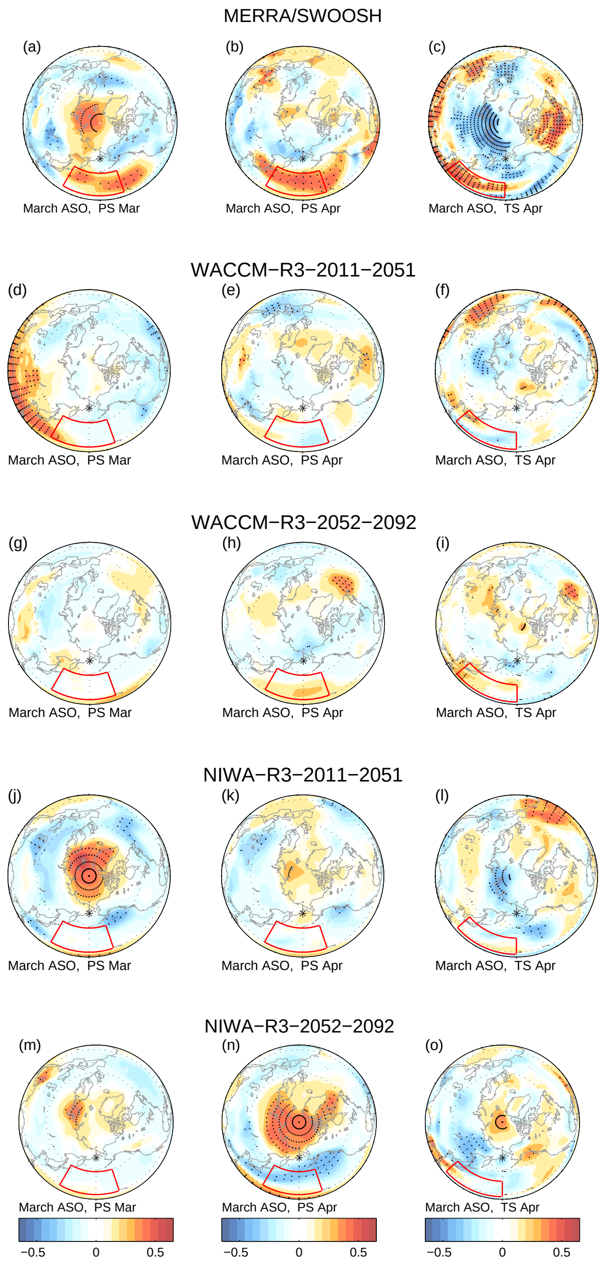

Figure 5. Correlation coefficient between ASO and sea-level pressure (PS) or surface temperature (TS), for MERRA/SWOOSH, WACCM-R3, and NIWA-R3, where R3 indicates the third realization. The left and center columns represent the correlation between ASO and sea-level pressure. The region of interest discussed in section 4 is marked by the red frame, and is defined by 20-50N and 150-200W. The leftmost column shows the correlation between the March ASO and March surface pressure, and the center column shows the correlation between the March ASO and April surface pressure. The rightmost column shows the correlation between the March ASO measurements/estimations and the April near-surface temperature. The region of interest discussed in section 4 is marked by a red frame, and is defined by 15-40N and 130-180W. In all the plots, the black dots mark the areas in which the correlation reaches statistical significance. The contour interval is 0.065

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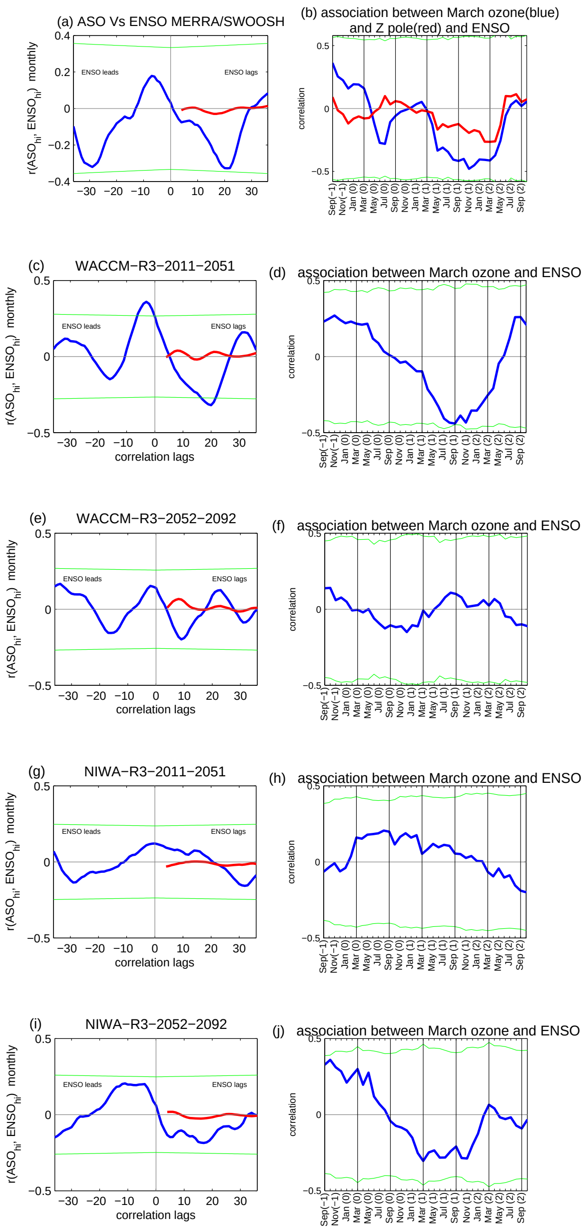

Figure 6. Lagged-correlation between ASO and ENSO for (a-b) MERRA/SWOOSH, (c-f) WACCM-R3, (g-j) NIWA-R3. The left column shows the lagged-correlation for all calendar months, and the right column shows the association between March ASO of every year and ENSO of every month across all years. The green lines mark the student's t-test 95% confidence level - the area above and under the green line indicate statistical significance of the correlation. The red line marks the minimal useful correlation, except for subplot (b) in which the red line represents the correlation between March polar geopotential height and ENSO.

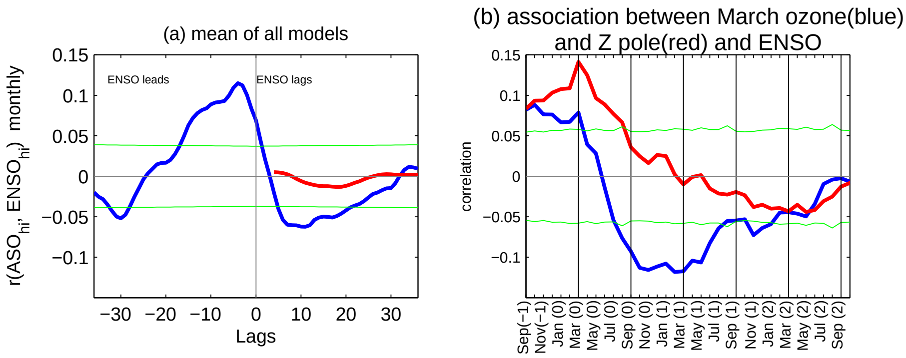

Figure 7. As in Figure 6 but for the multi-model mean.

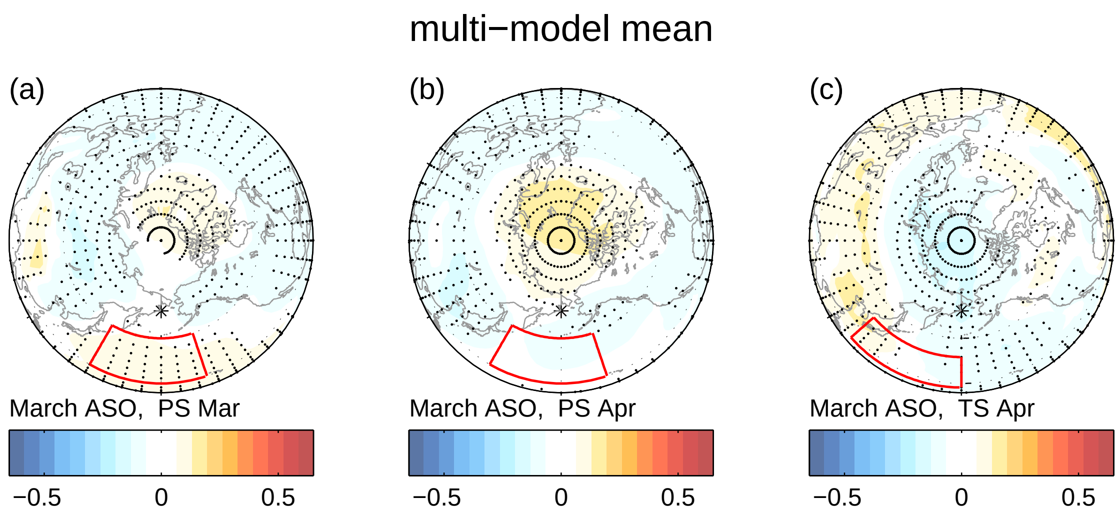

Figure 8. As in Figure 5 but for the Multi-model Mean.

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